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DESIGN AND PRELIMINARY TESTING OF A BRAYTON SPACE RADIATOR CONCEPT

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16. Abstract

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SUMMARY

A low-temperature radiator has been designed to reject 17.62 kilowatts of thermal power from an isotope Brayton power system. This power system has an electrical output of 7.1 kilowatts. The total radiator consists of two radiators connected in series. Both radiators have a redundant coolant loop, shared fins, and are close to flight configuration. A silicone oil with a viscosity of 2×10^{-6} square meters per second (2 cS) at 298 K (537° R) is used as the working fluid.

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The low-temperature radiator has an inlet temperature of 314 K (565° R), an outlet temperature of 295 K (531° R), an effective Reynolds number of 469, a mass of 232 kilograms (511 lb), and an area of 27.1 square meters (292 ft^2) to reject 5.55 kilowatts of thermal power.

INTRODUCTION

A Brayton cycle power system is now being developed at the NASA Lewis Research Center for generating electric power for future space missions (refs. 1, 2, and 3). The power system is a closed-cycle gas loop with a turbine, compressor, alternator, heat source, recuperator, and heat rejection system. The power system has an electric output of 7.1 kilowatts when provided with 25 kilowatts of thermal power from an isotope heat source.

A Brayton power system has completed over 2500 hours of successful operation in vacuum with an electric heat source and a facility heat rejection system in the Space Power Facility at Plum Brook Station of the Lewis Research Center (refs. 2 and 3). The next step in the combined system is to couple the power system to a fixed-area, flight-type, heat-rejection system, a space radiator.

The main emphasis of this report is on the design of a low-temperature space radiator to reject 17.62 kilowatts of thermal power corresponding to the 25 thermal kilowatt isotope Brayton power system conditions.

DESIGN GUIDELINES

There are three main areas that dictate requirements which must be taken into account in the radiator design: Brayton power system, physical configuration, and mission.

Brayton Power System

The power-system parameters that influence radiator design were obtained experimentally and are listed in table I. These data were obtained from tests of the Brayton power system with an electrical heat source and a radiator simulator. The coolant used is a silicone fluid with a viscosity of 2×10^{-6} square meters per second (2 cS) at 298 K (537° R). In order to minimize the area, and therefore the weight required to reject the power-system waste heat, the radiator is made up of two radiators connected in series (figs. 1 and 2), each with a pressure drop of approximately 103 420 newtons per square meter (15 psi). The series configuration reduces the total radiator area by about 15 percent. The high-temperature radiator takes advantage of the higher-temperature coolant fluid from the waste-heat-exchanger outlet. This fluid is at a temperature of 414 K (746° R) and is flowing at a rate of 0.0635 kilogram per second (0.14 lb/sec). When the temperature of this fluid reaches 314 K (565° R), it passes into a manifold where it mixes with the coolant fluid from cold plates and alternator cooling, which is also at

approximately 314 K (565° R). By mixing the fluid at this point, the Reynolds number inside the ducts is increased to a more desirable level. The fluid from this manifold is at 314 K (565° R), with a flow rate of 0.163 kilogram per second (0.36 lb/sec); these then are the low-temperature radiator inlet conditions. The low-temperature radiator outlet temperature of 295 K (531° R) is necessary to ensure a gas-system compressor inlet temperature of 300 K (540° R), which is a design condition for the power system.

The combination of the relatively low thermal power rejected, the large temperature drop in the Brayton system, and the low pump head available leads to relatively low coolant flows in the heat-rejection system. This low flow must be spread through the tubes of a fairly large radiator such that the pressure drop in the tubes is about 103 420 newtons per square meter (15 psi). The result of these restrictions is that the flow in the radiator tubes is laminar, which is undesirable for good heat transfer.

Physical Configuration

The physical configuration of the radiator must be set before the design calculations can be made. With laminar flow in the radiator tubes, it is desirable to use tubes with a large surface area for maximum heat transfer but with small cross-sectional areas to keep the Reynolds number as high as possible. One means of achieving this is to put some type of fins inside of conventional tubing. However, these types of tubing are expensive and difficult to assemble into a space-radiator configuration. The trapezoidal tube geometry shown in figure 3 is another way of achieving a large heat-transfer area with a small flow area. In addition, this tube geometry can be readily fabricated into radiator panels at reasonable cost.

The tube cross section is generally a slightly flattened segment of a circle which can be closely approximated by a trapezoid. The trapezoidal cross section shown in figure 3 has a combination of the properties of the three circular cross sections shown in the figure. A tube with the trapezoidal cross section has the same Reynolds number as the round tube of equivalent hydraulic diameter, the same pressure drop for equivalent Reynolds number as the round tube with equivalent cross-sectional area, and the same heat transfer area per unit length as the round tube with the equivalent perimeter.

Mission

The radiator is also to be as close to flight configuration as possible. This includes meteoroid protection, correct thermal mass for transient response, flight type emissivity coating, and physical dimensions. The mission influences the meteoroid protection

and the physical dimensions of the radiator. The mission requirements are 5-year operation with a 0.99 total probability of no failures due to tube puncture for a redundant-tube, shared-fin radiator. The radiator dimeter chosen is 6.6 meters (260 in.) in order to fit on a Saturn IVB section which is also the diameter of Skylab.

TRAPEZOIDAL TUBE PANEL TEST

Design hand calculations were performed to determine the feasibility of the trapezoidal tube radiator concept. It was found that limited information was available for either heat transfer or pressure drop for non-round shapes with laminar flow inside the channels. Therefore, a small-scale test was performed to evaluate the pressure drop and film temperature drop necessary for correlation to existing information.

The data presented in figures 4 and 5 are representative of the operating conditions of the high- and low-temperature radiators, respectively. Care must be taken in examining these data. The liquid temperatures were measured at the inlet and outlet of the radiator tube manifolds. Liquid temperatures entering and leaving each tube could not be measured. The fin root temperatures were calculated by means of a computer radiator design code. The tube bottom temperatures were measured along the middle tube of the 11 tubes in the panel. Since nearly all of the temperature drop is in the fluid film, the tube bottom temperature should be close to the fin root temperature. The panel test data are in good agreement with existing heat transfer correlations. The present design uses heat-transfer correlations available in the literature (ref. 4).

The pressure-drop data are in good agreement with predictions using the hydraulic diameter and trapezoidal flow area for correlating the data (fig. 6).

DESIGN

The final design for the trapezoidal-shape tube radiator for the 7.1-kilowatt-electric isotope Brayton power system was performed by means of a special computer radiator design code. Table I contains the design constraints for the isotope Brayton radiator. The Brayton power system has a separate redundant liquid cooling system for the waste heat exchanger, the Brayton rotating unit, and the electronic-equipment cold plates. The redundant cooling loop is activated in the event of a failure in the other coolant loop. To conserve radiator area, the radiator tubes for one coolant loop are placed between the tubes for the other coolant loop so that the two sets of tubes share a common fin radiating surface.

The use of shared fins reduces the meteoroid armor protection required. The overall design probability of no meteoroid punctures for a mission time of 5 years was set

at 0.99. This probability was distributed at 0.9950 for both the high-temperature and low-temperature radiators. Since the tubes for one coolant loop in the high- and low-temperature radiators can fail during the mission without affecting the power output of the Brayton system, the radiator tubes are designed to a no-failure probability of 0.9292 (ref. 5). Meteoroid armor thickness was calculated by the method of reference 6, and meteoroid flux data were obtained from reference 7.

Initial estimates indicated the total radiator area would be about 55.8 square meters (600 ft^2). The selection of 6.6 meters (260 in.) for the radiator diameter restricted the circumferential length of both radiators (connected in series) to about 18.3 meters (60 ft) (this allows for a gap of about 2.4 meters (8 ft) for the isotope heat source). With these restrictions and to reduce the number of welds needed to assemble the radiator, four 0.762-meter-wide (2.5-ft-wide) panels were arranged, with the radiator tubes running circumferentially, as shown in figure 2.

For the above design conditions, a parametric analysis of the primary and secondary radiators was conducted. The weights and areas of these radiators were determined as functions of the number of active tubes per panel, the height and width of the trapezoidal tubes, and fin thickness. Fin thickness was restricted to a minimum of 0.76 millimeter (0.030 in.) for fabrication reasons.

Figure 7 shows the results of this analysis. The numbers along each curve are the number of active tubes per 0.762-meter (2.5-ft) panel; each radiator has four parallel panels. The radiator weight plotted on the ordinate includes the weights for the redundant tubes and headers. The parameter X_1 is the ratio of tube height to tube width, and the parameter X_2 is the ratio of the short to the long widths of the trapezoidal tubes (see table II). The tube width varies with the number of tubes so that a maximum pressure drop of 103 420 newtons per square meter (15 psi) is not exceeded in either radiator.

To simplify fabrication, the high- and low-temperature radiators are restricted to having the same number of tubes per panel. Since the width of the radiators is 3.05 meters (10 ft), the area of the total radiator that corresponds to a length of 18.3 meters (60 ft) is 55.8 square meters (600 ft^2). Therefore, from figure 8, it is apparent that at least five active tubes per panel must be used to keep the total radiator length below 18.3 meters (60 ft). As a compromise between mass and area, six active tubes per panel were selected for the final design.

A summary of radiator design results is presented in table II. Some of the data in table II differ slightly from those in figures 7 and 8 because the final design dimensions were rounded out to convenient numbers after the parametric analysis was completed.

RADIATOR ASSEMBLY

The radiator panels were made by sandwiching, at the tube location, stop-weld material between two sheets of aluminum. A diffusion bond welds the aluminum sheets together where there is no stop-weld material. The tubes are then formed by pressurizing the stop-weld sections to separate the two sheets of aluminum, resulting in an approximately trapezoidal tube shape. The final radiator panel geometry is obtained from this process by having one sheet of aluminum equal the armor thickness and the other sheet equal the fin thickness (fig. 9). The excess armor between the tubes is then removed to expose the radiator fin. The maximum available size of the expanded tube panel is approximately 2.7 meters by 0.9 meter (9 by 3 ft). In order to use these panels to build up the circumferential tube radiator, the following assembly sequence was used.

The actual radiator assembly is made of four rows of panels (fig. 2) configured into a diameter of 6.6 meters (260 in.), with an opening large enough to accommodate a 25-thermal kilowatt isotope heat source. Each panel before assembly consists of open tubes at one end and redundant headers at the other end; the headers are welded to the flat armor, which has holes drilled into the flow channels (fig. 9). The final step before assembly is to butt-weld together the passages of two single panels as shown in figure 2. This is done by (1) expanding the ends of the channels to accept semicircular chill rings, (2) inserting a stainless steel chill ring into the channels of one panel shown in figure 9, (3) coupling a panel with chill rings, and (4) welding all channels so that they are leak-tight. Assembly of these panels for the test at the Space Power Facility is accomplished by hanging the top row of panels from a 6.6-meter-diameter (260-in.-diam) frame by means of compression springs to keep conduction heat loss to a minimum. The other rows of panels are then connected by welding into position. The final step in the radiator assembly is connecting the headers and manifolds. Since the tandem radiator has a separate set of redundant coolant channels, there are a total of six manifolds, consisting of two high-temperature inlet manifolds, two low-temperature inlet manifolds, and two outlet manifolds. As can be seen in figure 1, the outlet from the high-temperature radiator mixes with the coolants from the Brayton rotating unit and electronic-equipment cold plates before entering the headers of the low-temperature radiator.

After the radiator is completely assembled, a white emissive coating is sprayed over the outer surface. The location of the radiator with respect to the Brayton engine and cold wall for the ground test at the Space Power Facility is shown in figure 10.

SUMMARY OF RESULTS

A radiator has been designed for the 7.1-kilowatt-electric isotope Brayton power system to operate in the laminar flow regime and to reject 17.62 kilowatts of thermal

power. The total radiator consists of a high-temperature radiator and a low-temperature radiator connected in series. The total radiator has been designed for a 5-year mission with 0.99 probability of no failure due to meteoroid puncture for the redundant-tube, shared-fin case. A trapezoidal coolant tube is used in both radiators.

Small-scale tests were run to determine the applicability of existing heat-transfer and pressure-drop correlations for round tubes to the trapezoidal tube. The results of these tests are in good agreement with these existing correlations.

The high-temperature radiator has an inlet temperature of 414 K (746° R), an outlet temperature of 314 K (565° R) an effective Reynolds number of 648, a mass of 156 kilograms (344 lb) including meteoroid armor, and an area of 26.1 square meters (281 ft) to reject 12.07 kilowatts of thermal power. The low-temperature radiator has an inlet temperature of 314 K (565° R), an outlet temperature of 295 K (531° R), an effective Reynolds number of 469, a mass of 232 kilograms (511 lb), and an area of 27.1 square meters (292 ft^2) to reject 5.55 kilowatts of thermal power.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 20, 1971,
112-27.

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TABLE I. - RADIATOR DESIGN CONSTRAINTS FOR ISOTOPE

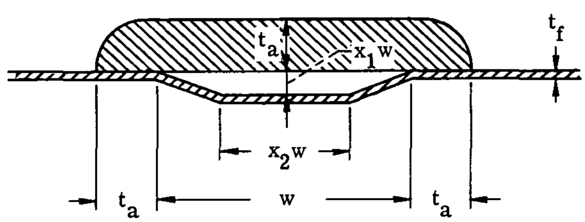
BRAYTON POWER SYSTEM

[Overall radiator consists of two radiators connected in series, with two identical, redundant, coolant loops, and with circumferential tubes and shared fins.]

	High-temperature radiator	Low-temperature radiator
Coolant flow rate, kg/sec (lbm/sec)	0.0635 (0.14)	0.163 (0.36)
Maximum pressure drop, N/m^2 (psi)	103 420 (15)	103 420 (15)
Inlet temperature, K (^oR)	414 (746)	314 (565)
Outlet temperature, K (^oR)	314 (565)	295 (531)
Heat rejected, kWt	12.07	5.55
Sink temperature, K (^oR)	250 (450)	250 (450)
Emissivity	0.88	0.88
Coolant	Silicone oil	
Coolant viscosity at 298 K (537^o R), m^2/sec (cS)	2×10^{-6} (2)	
Overall no-puncture probability	0.99	
Mission time, yr	5	
Overall radiator diameter, m (in.)	6.6 (260)	

TABLE II. - FINAL DESIGN SPECIFICATIONS FOR

EXPANDED-TUBE RADIATOR



	High-temperature radiator	Low-temperature radiator
Tube bottom width, W, cm (in.)	0.96 (0.38)	1.78 (0.70)
Tube height, X_1W, mm (in.)	1.81 (0.032)	1.07 (0.042)
Tube top width, X_2W, cm (in.)	0.48 (0.19)	0.89 (0.35)
Armor thickness, t_a, cm (in.)	0.46 (0.18)	0.51 (0.20)
Fin thickness, t_f, mm (in.)	0.76 (0.03)	0.76 (0.03)
Number of tubes per panel	[a]12	[a]12
Radiator area, m^2 (ft^2)	26.1 (281)	27.1 (292)
Radiator mass, kg (lb)	156 (344)	232 (511)
Pressure drop, ΔP, N/m^2 (psi)	94 458 (13.7)	100 664 (14.6)

[a]Six active and six inactive.

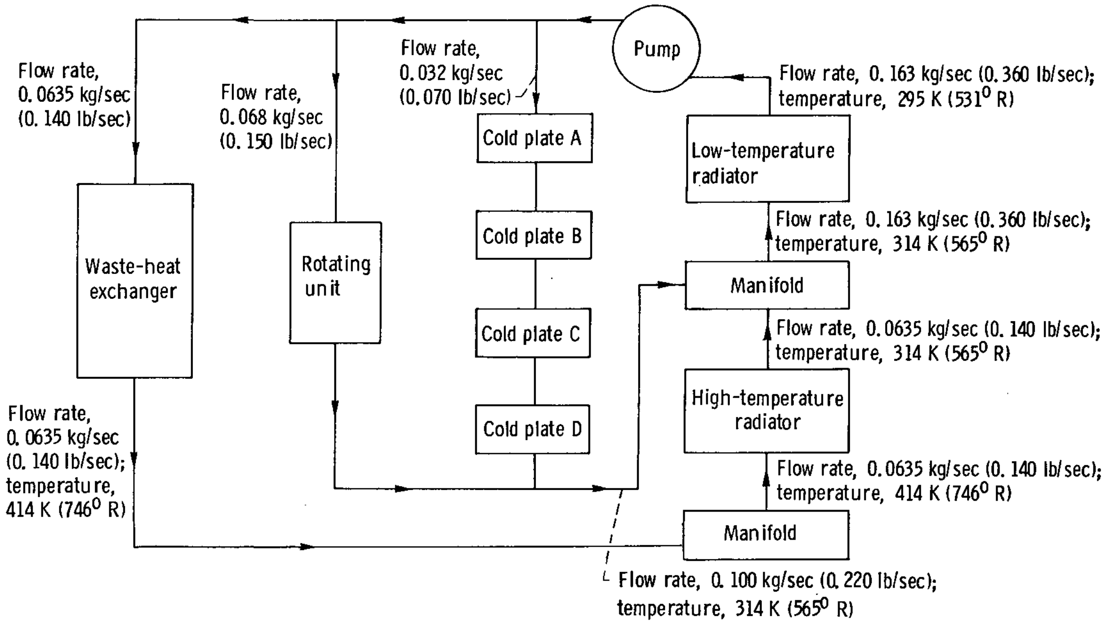


Figure 1. - Brayton cycle coolant-loop schematic.

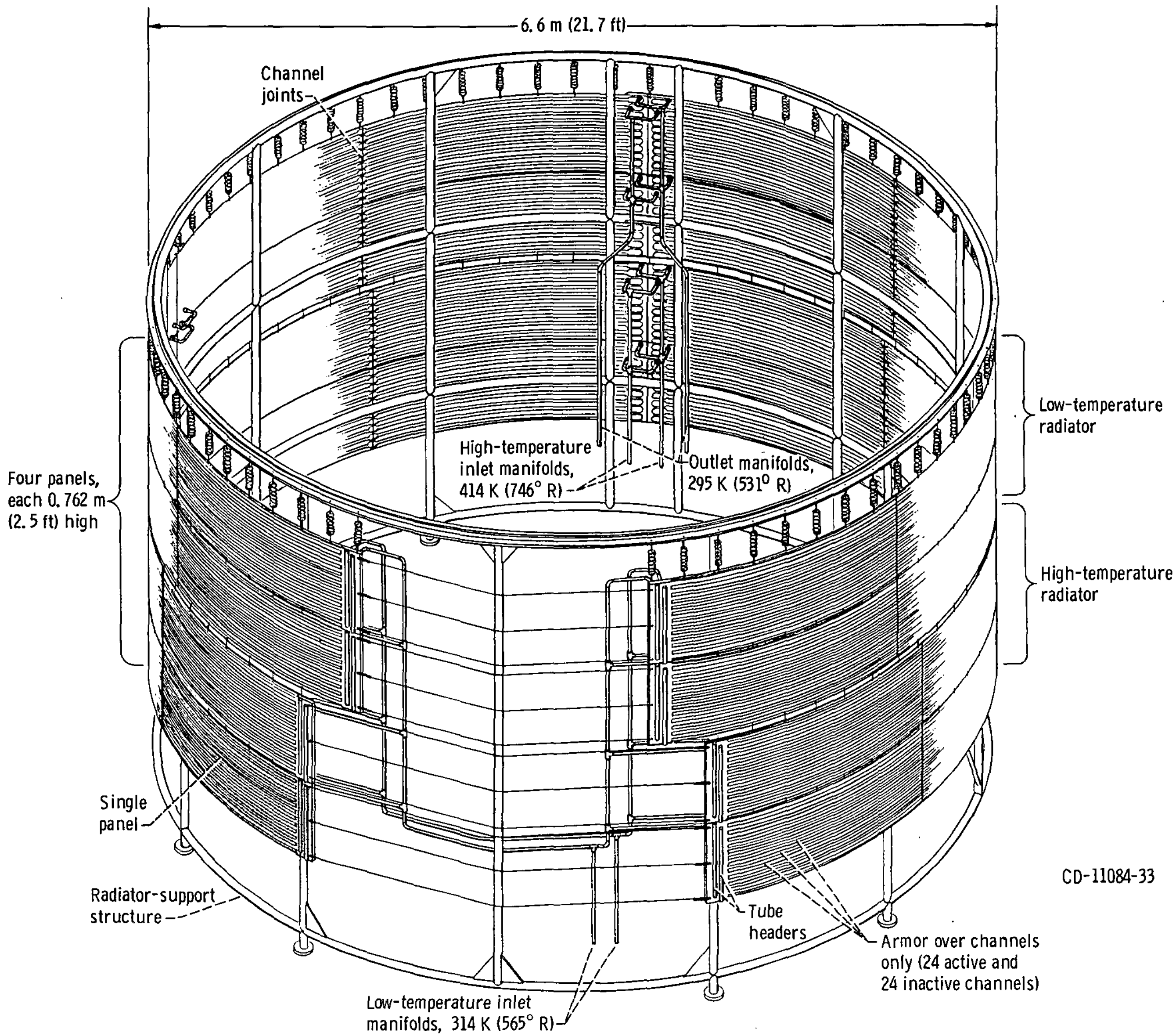


Figure 2. - Brayton-cycle radiator details.

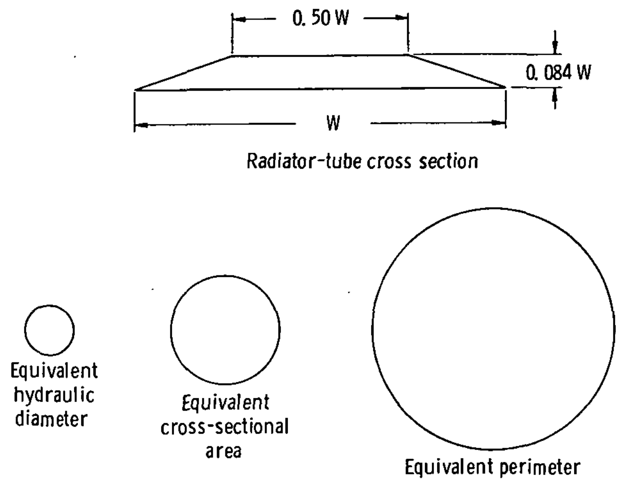


Figure 3. - Comparison of radiator-tube trapezoidal cross section with circular cross sections.

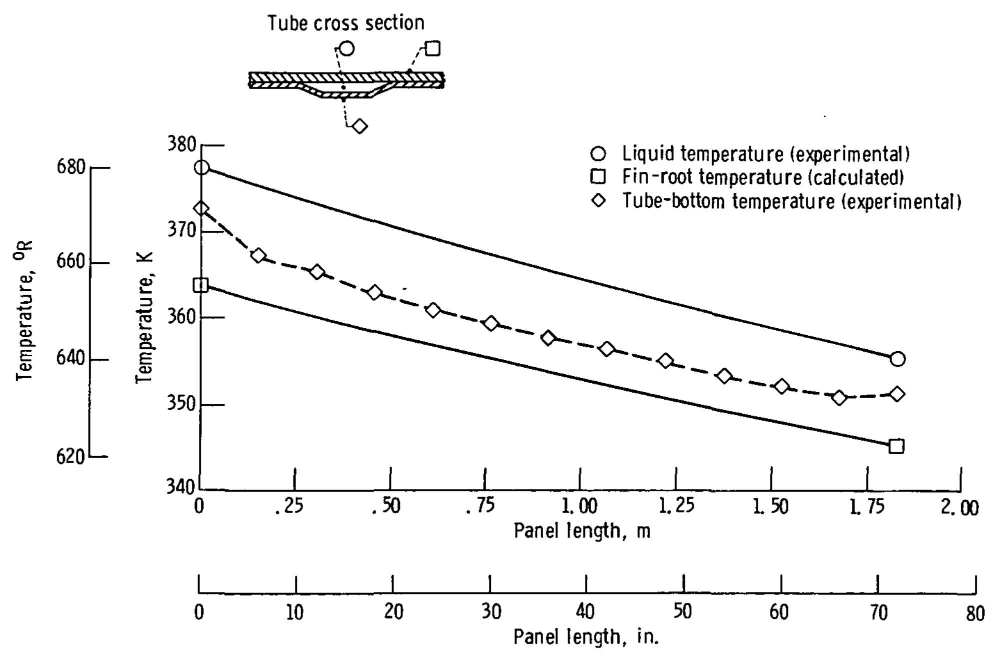


Figure 4. - Panel-test data showing tube-temperature profile for high-temperature radiator. Sink temperature, 261 K (470° R).

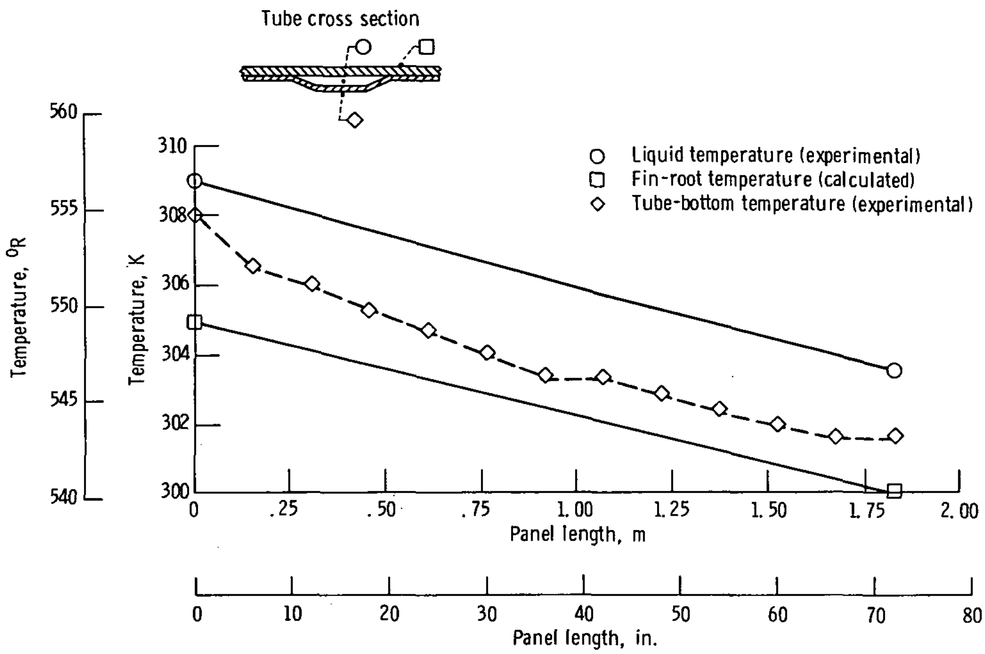


Figure 5. - Panel-test data showing tube-temperature profile for low-temperature radiator. Sink temperature, 255 K (459° R).

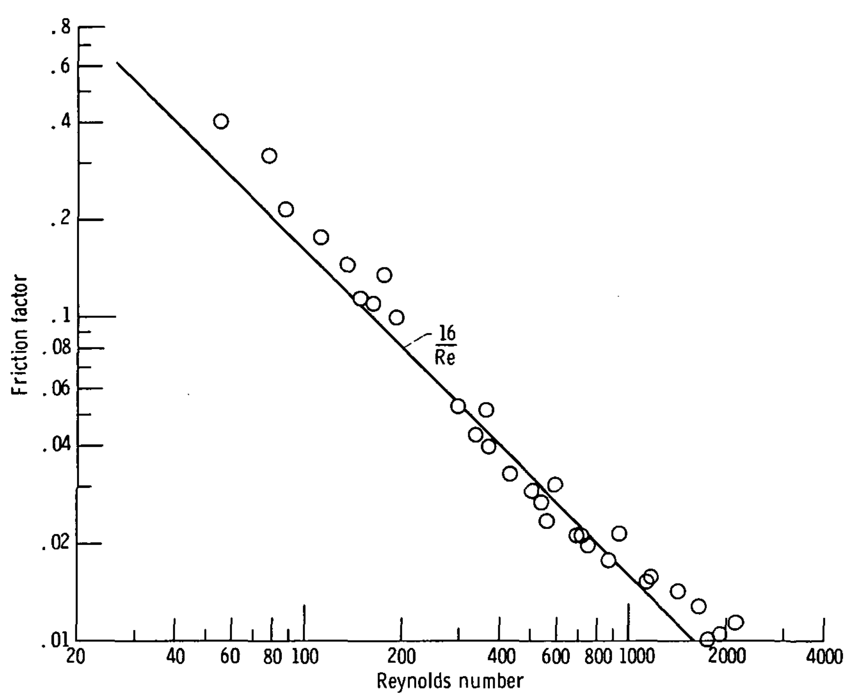


Figure 6. - Panel-test data showing friction factor as a function of Reynolds number.

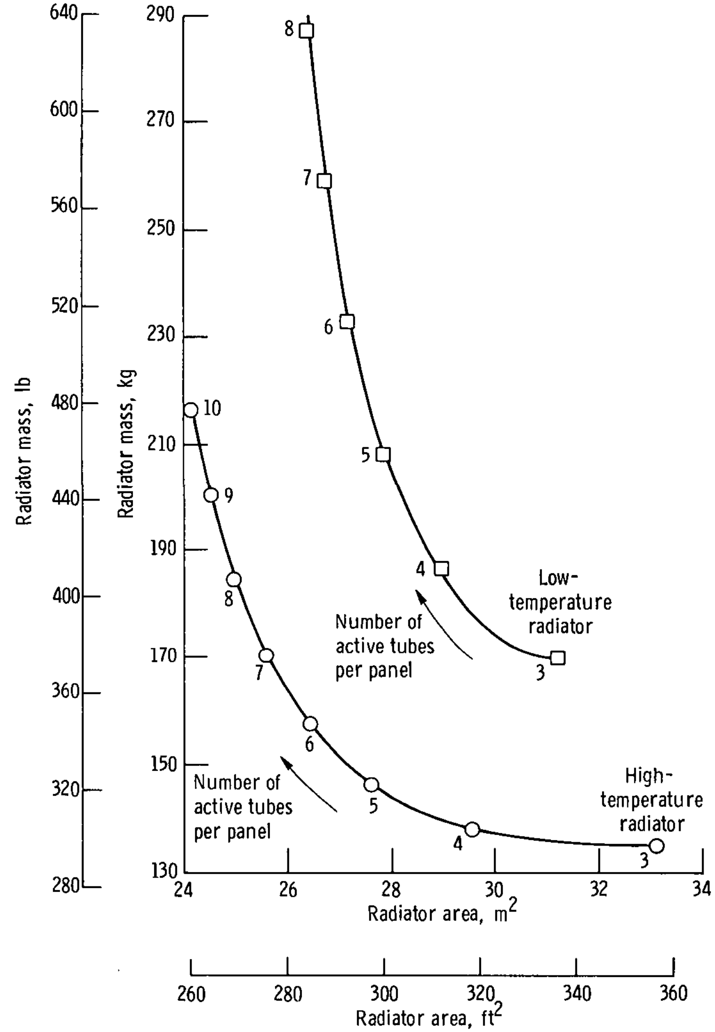


Figure 7. - Brayton power system radiator weight as a function of radiator area for high- and low-temperature radiators. Shared-fin configuration; probability of no puncture for each radiator, 0.995; mission duration, 5 years; fin thickness, 0.76 millimeter (0.030 in.); pressure drop in each radiator, 103 420 newtons per square meter (15 psi); sink temperature, 250 K (450° R).

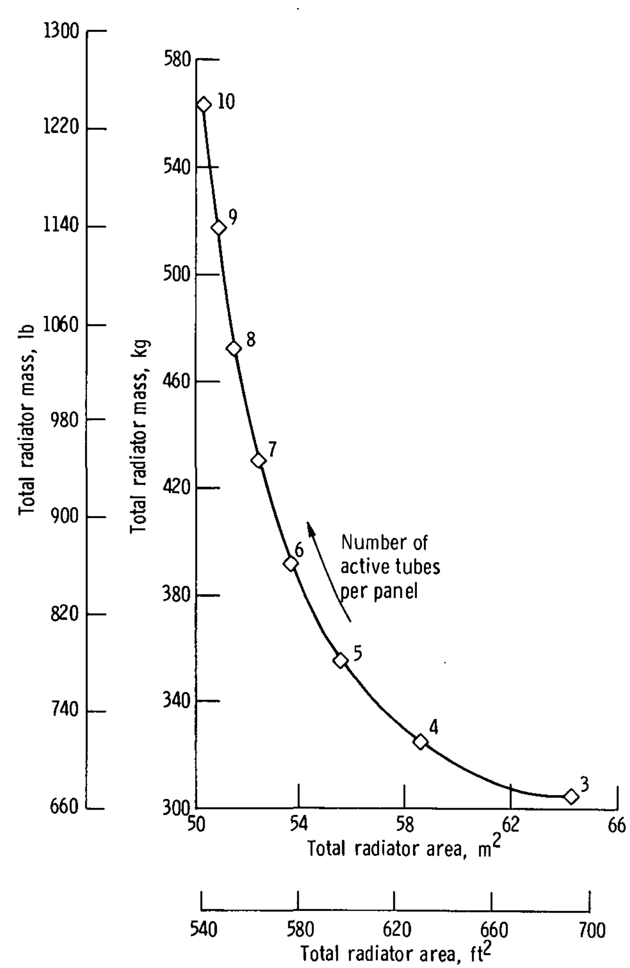
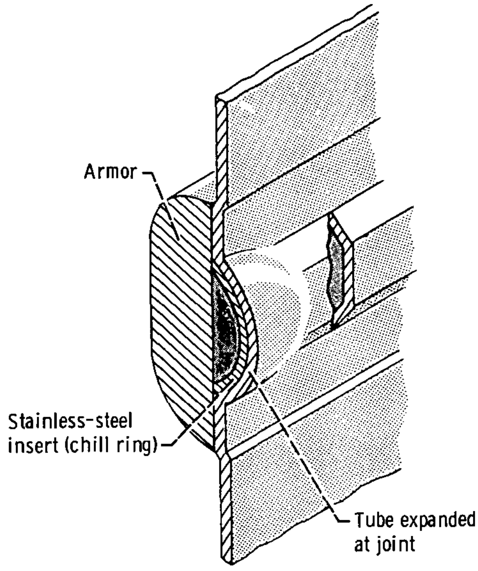
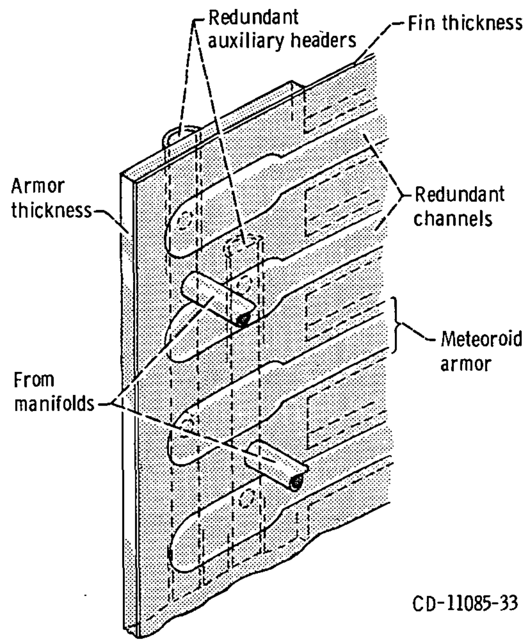


Figure 8. - Brayton power system total radiator weight as a function of total radiator area. Shared-fin configuration; probability of no puncture for total radiator, 0.99; mission duration, 5 years; fin thickness, 0.76 millimeter (0.030 in.); pressure drop, 103 420 newtons per square meter (15 psi); sink temperature, 250 K (450° R).



Channel joint



Radiator assembly
(inside view)

Figure 9. - Brayton cycle radiator.

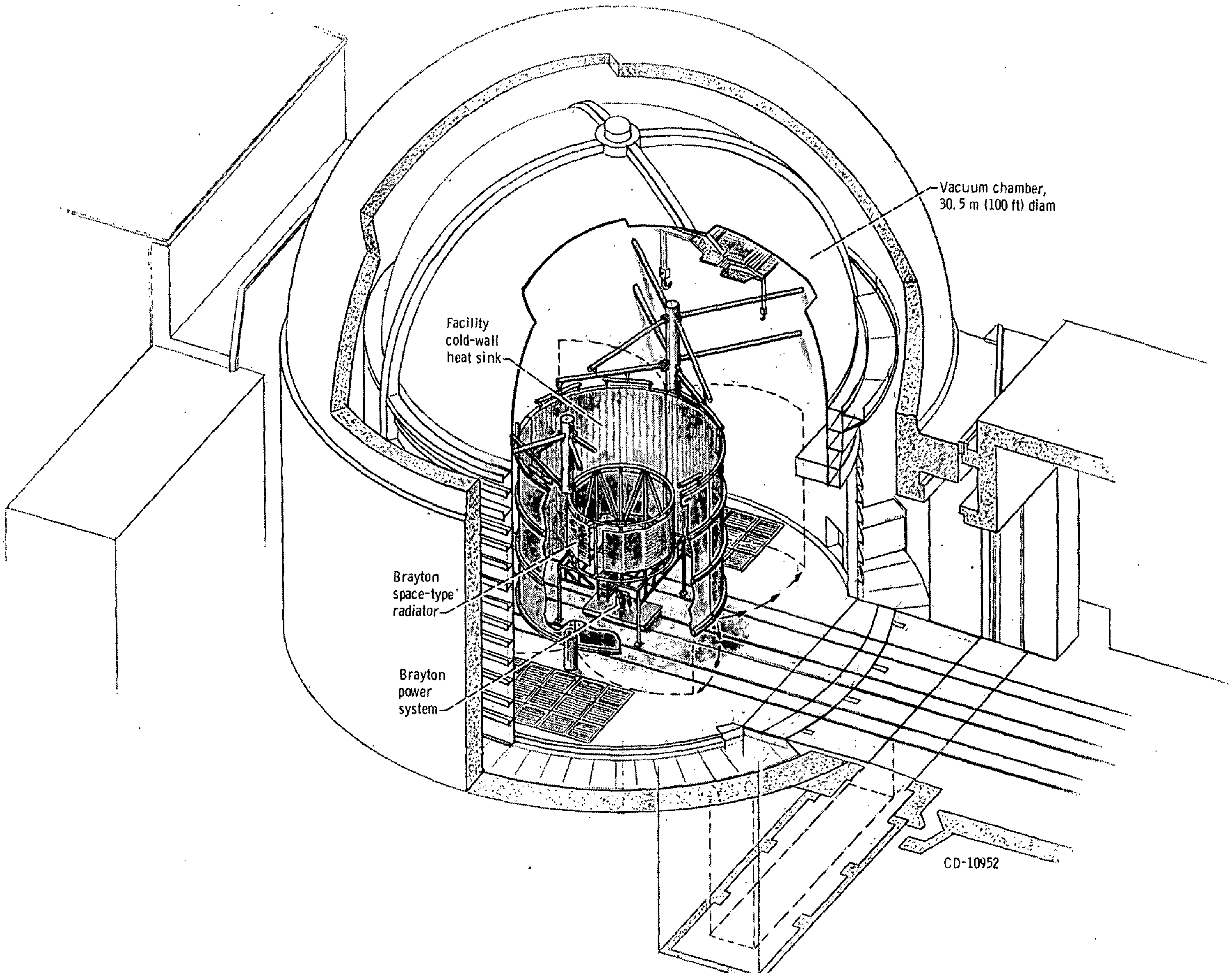


Figure 10. - Brayton power system installed for test in the Space Power Facility at Plum Brook Station of the Lewis Research Center.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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